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ORIGINAL ARTICLE

Self-healing of polymer modified concrete

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KEYWORDS

Cracks;
Self healing;
Polymer modified concrete;
Damage

Abstract Self healing phenomenon of concrete has been observed in traditional, fibrous, self compacting concrete. This phenomenon occurred mainly due to the presence of unhydrated cement particles in the presence of water. Mechanism of polymer in concrete depends on creating a layer and net of polymer around cement particles which enhances the properties of polymer modified concrete. This mechanism may affect the self healing of this type of concrete. This work aims to study the presence of the self healing phenomenon in polymer modified concrete and the related parameters. An experimental investigation on self healing of polymer modified concrete was undertaken. In this research work, effect of polymer type, polymer dose, cement content, cement type, w/cm ratio and age of damage were studied. The healing process extended up to 60 days. Ultrasonic pulse velocity measurements were used to evaluate the healing process. Results indicated that, the self healing phenomenon existed in polymer modified concrete as in traditional concrete. The increase of polymer dose increases the healing degree at the same healing time. This increase depends on polymer type. Also, the decrease of w/cm ratio reduces the self healing degree while the use of Type V Portland cement improves the self healing process compared with Type I Portland cement. Cement content has an insignificant effect on healing process for both concrete with and without polymer. In addition, the increase of damage age decreases the efficiency of self healing process.

1. Introduction

Concrete in service cracks due to direct stress and substress caused by many kinds of reasons, such as changes of temperature and humidity, inhomogeneous sinking and external loading (dynamic or static loading). Cracks not only influence the service durability of concrete structure, but also are harmful for the structure safety [12].

Self-healing phenomenon has been observed in cementitious materials for many years. One such example is on a famous bridge in Amsterdam, where micro cracks were self-healed by the recrystallization of calcite [8]. Self healing phenomenon also was observed in some other concrete structure

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Table 1 Description of used concrete mixes and studied parameters.

Mix no.	Polymer type	W/cm ratio	Polymer dose (%)	Cement content (kg/m^3)	Cement type	Studied parameters
1	SBR	0.40	0	500	Type I	Effect of dose of polymer (main group)
2	SBR	0.40	5	500	Type I	
3	SBR	0.40	10	500	Type I	
4	SBR	0.40	15	500	Type I	
5	SBR	0.40	0	600	Type I	Effect of cement content
6	SBR	0.40	10	600	Type I	
7	SBR	0.50	0	500	Type I	Effect of w/cm ratio
8	SBR	0.50	10	500	Type I	
9	SBR	0.40	0	500	Type V	Effect of cement Type
10	SBR	0.40	10	500	Type V	
11	ACR	0.40	0	500	Type I	Effect of type of polymer
12	ACR	0.40	10	500	Type I	
13	SBR	0.40	0	500	Type I	Effect of age of deterioration
14	SBR	0.40	10	500	Type I	

Table 2 Ultrasonic pulse velocity test results.

Mix no.	Specimen no.	UPV before healing (km/s)			UPV after healing (km/s)		
		Initial UPV	UPV after cracking	Damage level (%)	After 20 days	After 40 days	After 60 days
1	1	4.691	2.489	46.9	4.159	4.234	4.285
	2		2.862	39.0	4.311	4.364	4.391
	3		3.535	24.6	4.391	24.6	4.447
2	1	4.582	3.047	33.5	4.311	33.5	4.464
	2		1.425	68.9	2.688	68.9	3.391
	3		2.446	46.3	3.626	46.3	4.135
	4		3.483	24.0	4.337	24.0	4.532
3	1	4.449	3.822	14.1	4.291	14.1	4.364
	2		2.934	34.1	4.110	34.1	4.208
	3		2.862	35.7	4.010	35.7	4.135
4	1	4.419	3.009	31.9	4.040	31.9	4.337
	2		3.319	24.9	4.260	24.9	4.419
	3		3.449	21.0	4.470	21.0	4.503
5	1	4.842	3.721	23.2	4.479	23.2	4.634
	2		4.208	13.0	4.568	13.0	4.769
6	1	4.475	2.851	36.3	3.842	36.3	4.159
	2		2.751	38.5	3.781	38.5	4.089
	3		3.243	27.5	4.110	27.5	4.391
7	1	4.682	3.571	23.7	4.217	23.7	4.420
	2		3.214	31.4	4.210	31.4	4.261
	3		3.994	14.7	4.285	14.7	4.410
8	1	4.424	2.784	37.1	3.658	37.1	4.063
	2		2.898	34.5	3.761	34.5	4.115
	3		2.590	41.5	3.483	41.5	3.972
9	1	4.823	2.571	46.7	4.087	46.7	4.475
	2		2.909	39.7	4.237	39.7	4.651
	3		3.761	22.0	4.591	22.0	4.944
10	1	4.621	2.874	37.8	3.801	37.8	4.208
	2		3.047	34.1	4.063	34.1	4.447
11	1	4.567	3.228	29.3	4.264	29.3	4.411
	2		3.863	15.4	4.364	15.4	4.583
	3		3.415	25.2	4.337	25.2	4.559
12	1	4.394	3.128	28.8	4.135	28.8	4.370
	2		3.021	31.2	3.950	31.2	4.364
	3		2.828	35.6	3.850	35.6	4.235
13	1	4.538	4.100	9.7	4.510	9.7	4.600
	2		2.142	52.8	4.150	52.8	4.301
14	1	4.227	1.425	66.7	3.115	66.7	3.590
	2		2.682	37.3	4.087	37.3	4.331
	3		3.078	28.0	4.390	28.0	4.570

like waterproof concrete structure and concrete pipes this phenomenon. Waterproof concrete structures cracked and leaked gently at early ages, however, it seems that at later ages the cracks closed completely and leaking stopped. Reinforced concrete pipes that developed shrinkage crack up to 1.5 mm wide, and were subsequently put into service. Five years later, the cracks were found to be completely closed by autogenous healing [12]. Also, Sahmaran et al. [9] mentioned that self healing process observed in self consolidating concretes and this process enhanced mechanical properties of concrete. For mortars with steel fiber, it was observed that self healing can increase pullout resistance and compressive strength [6].

Self-healing of cracks is one phenomenon also acting positively in durability problems of concrete. This process can take place only in presence of water (dissolved CO_2 is not always needed), and consists of chemical reactions of compounds exposed at the cracked surfaces. These reactions produce crystals, and the accretion of these from the opposite surfaces of a crack can reestablish the continuity of the material eventually. The essential requirement, with water, is the presence of compounds capable of further reaction. Thus, cement, hydrated or not, is the essential reactive element. There are two major assumptions regarding the reactions of healing [5]: the hydration of unhydrated clinker available in the microstructure of hardened concrete (important for concrete with low water/cement ratio), or the precipitation of calcium carbonate $CaCO_3$. The first hypothesis requires only the presence of water, and the second one the presence of dissolved CO_2 in addition. Silting up of cracks or deposition of debris can contribute to healing but can not provide it by themselves [11]. From the literature review, in all cases, additional water is essential for the self-healing mechanism. This is not a problem for underground structures where water saturation generally exists. However, for above ground structures, the availability of water is limited [4] .

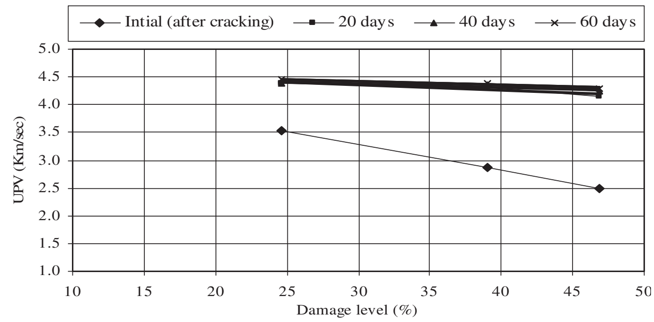
Polymer-modified concrete (PMC) has recently been called polymer Portland cement concrete (PPCC). According to ACI 548.3R, PMC is defined as Portland cement and aggregate combined at the time of mixing with organic polymers that are dispersed or redispersed in water. As the cement hydrates, coalescence of the polymer occurs, resulting in a co-matrix of hydrated cement and polymer film throughout the concrete.

The addition of polymers to Portland cement results primarily in improvements in adhesion, resistance to penetration of water, durability, and some strength properties. A wide variety of polymer types have been investigated for use in PMC, but the major types in use today are Styrene-butadiene copolymers, Acrylic ester homopolymers, Vinyl acetate copolymers and Vinyl acetate homopolymers [10].

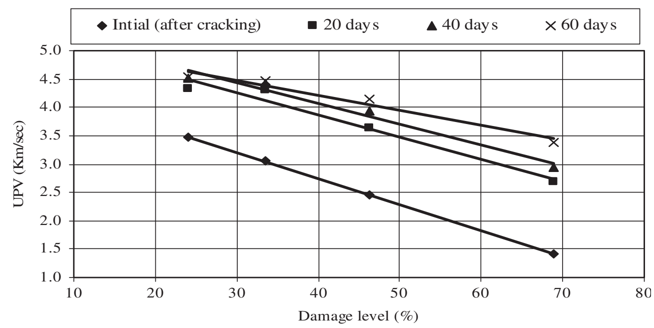
2. Materials and experimental program

2.1. Materials

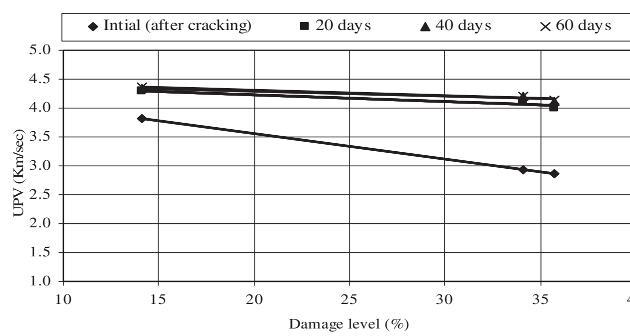
Crushed pink lime stone with nominal maximum aggregate size of 3/8 inch and natural siliceous sand of 2.60 fineness modulus were used. Two types of cement were used in this research work. These types were Type I and Type V Portland cement according to ASTM C150. Styrene butadiene rubber and acrylic as two famous types of polymers in construction market were used. The solid content of these types is about 52%. A high range water reducing admixture, ASTM Type F, was used to achieve concrete workability.



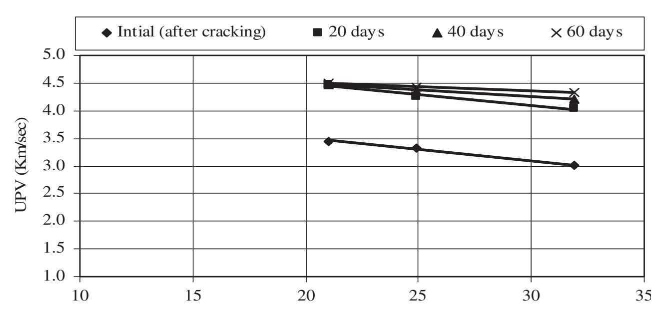
a- Control mix (Mix No. 1)



b- 5 % SBR (Mix No. 2)



c- 10 % SBR (Mix No. 3)



d- 15 % SBR (Mix No. 4)

Figure 1 Correlation between damage level and UPV (Mixes 1–4).

2.2. Test parameters

In this study, six parameters were studied. These parameters were polymer dose, polymer type, cement content, cement type, w/cm ratio and age of concrete damage. The used polymers were styrene butadiene rubber (SBR) and

Table 3 Statistical parameters for different concrete mixes at different healing times.

Mix no.	Healing time (days)	C_1	C_2	R^2	Mix no.	Healing time (days)	C_1	C_2	R^2
1	0	4.6889	0.0469	1.000	8	0	4.4165	0.0440	1.0000
	20	4.6484	0.0098	0.8862		20	5.1315	0.0397	1.0000
	40	4.5637	0.0064	0.7408		40	5.5908	0.0495	1.0000
	60	4.6267	0.0069	0.8869		60	4.8212	0.0205	0.9999
2	0	4.5807	0.0459	0.9999	9	0	4.8209	0.0482	1.0000
	20	5.4324	0.0392	0.9652		20	5.0396	0.0204	0.9999
	40	5.5218	0.0365	0.9683		40	4.9766	0.0143	0.9659
	60	5.2714	0.0264	0.9655		60	5.3590	0.0185	0.9896
3	0	4.4484	0.0444	1.0000	10	0	4.6414	0.0468	1.0000
	20	4.4539	0.0113	0.9170		20	6.4776	0.0708	1.0000
	40	4.4504	0.0084	0.9008		40	5.9683	0.0516	1.0000
	60	4.4990	0.0094	0.9384		60	6.6497	0.0646	1.0000
4	0	4.3179	0.0408	0.9952	11	0	4.5666	0.0457	1.0000
	20	5.2551	0.0385	0.9779		20	4.4704	0.0064	0.7768
	40	4.9653	0.0238	0.9972		40	4.7176	0.0120	0.9987
	60	4.8038	0.0148	0.9715		60	4.7638	0.0106	0.6559
5	0	4.8397	0.0482	1.0000	12	0	4.3972	0.0411	1.0000
	20	4.6834	0.0088	1.0000		20	5.2385	0.0395	0.8896
	40	4.7058	0.0059	1.0000		40	5.1218	0.0281	0.8969
	60	4.9441	0.0134	1.0000		60	4.9928	0.0210	0.9034
6	0	4.4718	0.0447	1.0000	13	0	4.5407	0.0454	1.0000
	20	4.9362	0.0301	0.9998		20	4.5910	0.0084	1.0000
	40	5.0633	0.0283	0.9997		40	4.6389	0.0080	1.0000
	60	5.1386	0.0271	0.9989		60	4.6675	0.0070	1.0000
7	0	4.6799	0.0467	1.0000	14	0	4.2748	0.0427	1.0000
	20	4.3438	0.0046	0.8526		20	5.3148	0.0330	1.0000
	40	4.5117	0.0079	0.9778		40	5.3517	0.0326	0.9989
	60	4.5647	0.0086	0.6580		60	5.2767	0.0253	1.0000

acrylic (ACR). The studied doses of styrene butadiene rubber were 5.0%, 10.0% and 15.0% by weight of cement while the dose of acrylic only 5.0% and 10.0% by weight of cement were studied. Two studied cement contents were studied. These contents were 500 and 600 kg/m^3. The used w/cm ratios were 0.40 and 0.50 and the studied age of damage were 7 and 28 days. The experimental program involves 14 concrete mixes. Table 1 summarizes the used concrete mixes and test parameters.

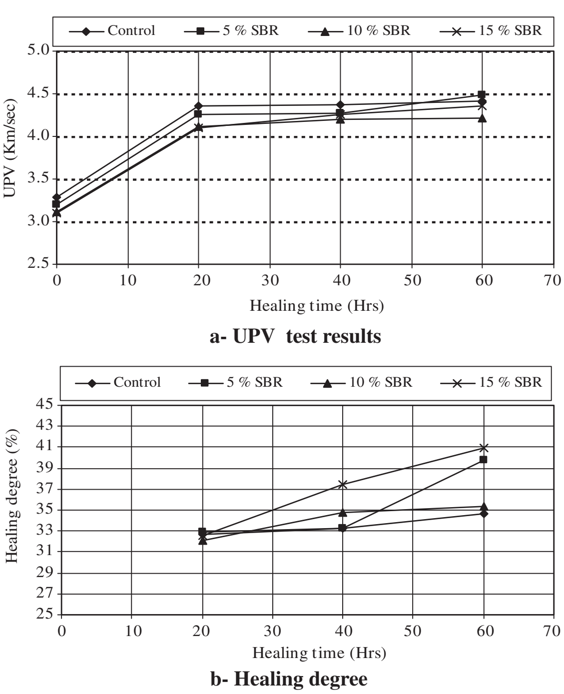


Figure 2 Effect of SBR on UPV and healing degree at 30.0% damage level.

2.3. Specimens and test procedures

Cubes of $10.0 \times 10.0 \times 10.0$ cm were used through this research. After being casting, specimens were demolded after 1 day and then they were cured in potable water for other 5 days. This method was suggested by Ohama [7] for polymer modified concrete [7]. At age of 28 days ultrasonic pulse velocity (UPV) was measured and then concrete specimens were loaded up to ultimate loads. Only one group was tested at 7 days. After loading process, ultrasonic pulse velocity was measured again. Self healing process was taken place using three stages in water immersion and every stage extended to 20 days. So, the healing times of this research work were 20, 40 and 60 days of water immersion. Ultrasonic pulse velocity technique was used to evaluate self healing phenomenon. This method was approved by Zhong and Yao [12]. Thermogravimetric analysis was used to estimate degree of hydration.

3. Test results and discussions

3.1. Experimental test results

Table 2 includes initial ultrasonic pulse velocity ($UPV_{initial}$), ultrasonic pulse velocity after cracking ($UPV_{cracked}$), ultrasonic pulse velocity after each stage of healing process and the damage level for each specimen. The percentage of damage level is calculated as follow:

$$\text{Damage level } (\%) = [1 - (\text{UPV}_{\text{cracked}}/\text{UPV}_{\text{initial}})] \times 100 \quad (1)$$

From this table, self healing phenomenon can be observed by following ultrasonic pulse velocity test results for concrete mixes along healing time. It can be seen clearly that the ultrasonic pulse velocity increases with the increase of healing time. This trend is the same for both control mixes and polymer modified concrete mixes.

3.2. Relation between damage level and UPV

There is no constant damage level for all concrete mixes as shown in Table 2. This constant damage level is needed to make a reliable comparison to study the effect of studied parameters in this research work. Experimentally, it is very difficult to achieve this constant damage level. Therefore, relations between damage level and ultrasonic pulse velocity for all concrete mixes are constructed. Fig. 1 gives examples for these relations for concrete mixes made with 500 kg/m^3 Type I Portland cement, 0.40 w/cm ratio and 0.0, 5.0, 10.0 and 15.0 styrene butadiene rubber. These specimens were tested under compression at the age of 28 days.

The pervious relations can be used to estimate ultrasonic pulse velocity corresponding to any certain damage level after any healing time. To make this method easier, empirical mathematical model between damage level and ultrasonic pulse velocity is used. Least square method is used to select the best model for these test results. So, as shown in Fig. 1, straight line model seems to be a suitable and simple model because it yields the highest values of R^2. The general equation for this model can expressed as:

$$\text{UPV} = C_1 D - C_2 \quad (2)$$

where D is the damage level (%), and C_1 and C_2 are equation constants. Values of C_1, C_2 and R^2 for all tested concrete mixes are listed in Table 3.

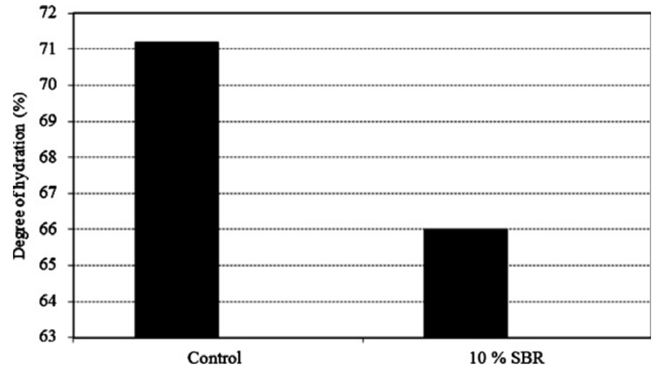


Figure 4 Degree of hydration of mixes with 0% and 10.0% styrene butadiene rubber after 28 days.

3.3. Effect of polymer dose

To study the effect of any studied parameters, a constant damage level is needed. Thirty percentage damage is chosen because this level generally exists in most studied concrete mixes. Fig. 2a shows relation between healing time versus

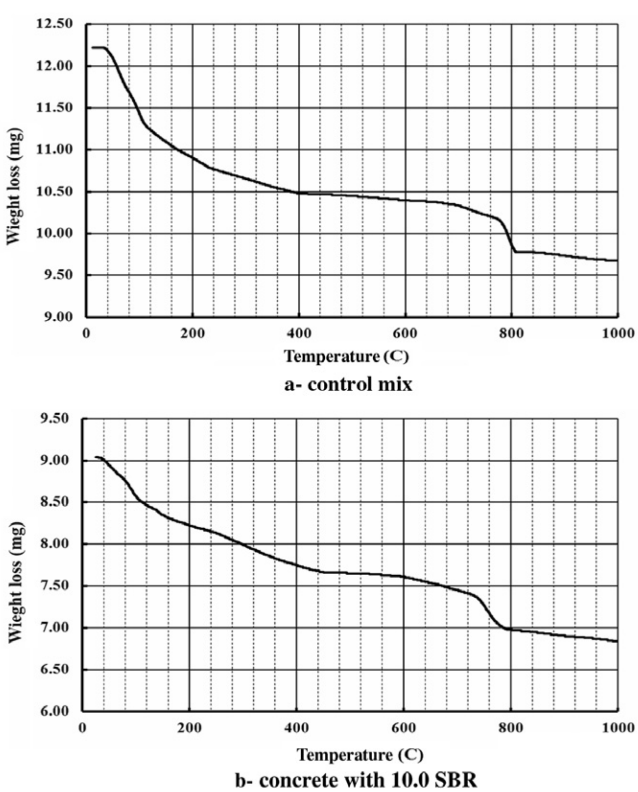


Figure 3 Results of thermogravimetric TGA.

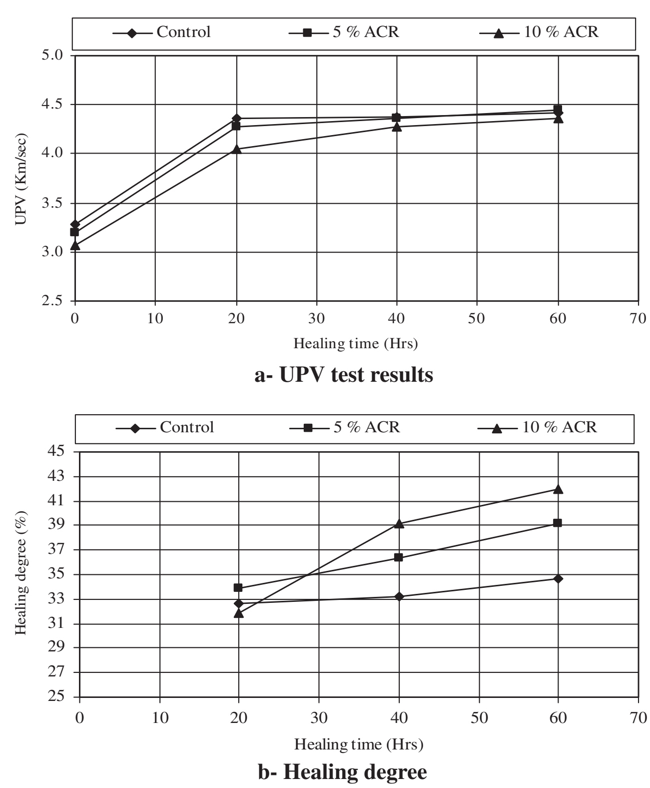


Figure 5 Effect of the incorporation of ACR on UPV and healing degree at 30.0% damage level.

ultrasonic pulse velocity for concrete mixes with 0.0%, 5.0%, 10.0% and 15.0% styrene butadiene rubber at 30.0% damage level. From this figure, the use of styrene butadiene rubber decreases the initial ultrasonic pulse velocity. Also, during the healing process, at any time, ultrasonic pulse velocity of concrete mixes with styrene butadiene rubber is still less than that of concrete mix. Also, it is clear that ultrasonic pulse velocity for all concrete mixes increases with the increase of healing time. This increase is noticeable after 20 days of healing time. After 20 days, the rate of healing process decreases compared with the rate of healing process before 20 days. Fig. 2b shows calculated healing degree which is defined as the percentage increase in ultrasonic pulse velocity as a result of self healing process based on ultrasonic pulse velocity results after cracking before self healing process.

From this figure, it is clear that, around 31% of healing degree is achieved after 20 days. After this period, healing degree for control mix remains constant with the increase of healing age. This means that the increase of healing time after 20 days has insignificant effect on increasing healing process. 20 days of healing time may be enough to convert most of unhydrated cement particles to hydrated particles. On the contrary, for polymer modified concrete mixes with styrene butadiene rubber. A continuous improvement in healing degree up to 60 days is noticeable. Also, it is clear that, at the same healing time, the increase of polymer dose increases healing degree when compared with control mix. This may be due to the membrane of polymer that covers cement particles which decreases the ingress of water to unhydrated cement particles or due to the increase of amount of unhydrated cement as a result of the presence of polymer in concrete. This behavior agrees with the same that proposed model by AC1 548.3R-2003 [1].

In additions, this mechanism is approved by thermogravimetric analysis test (TGA). TGA test was carried out on paste

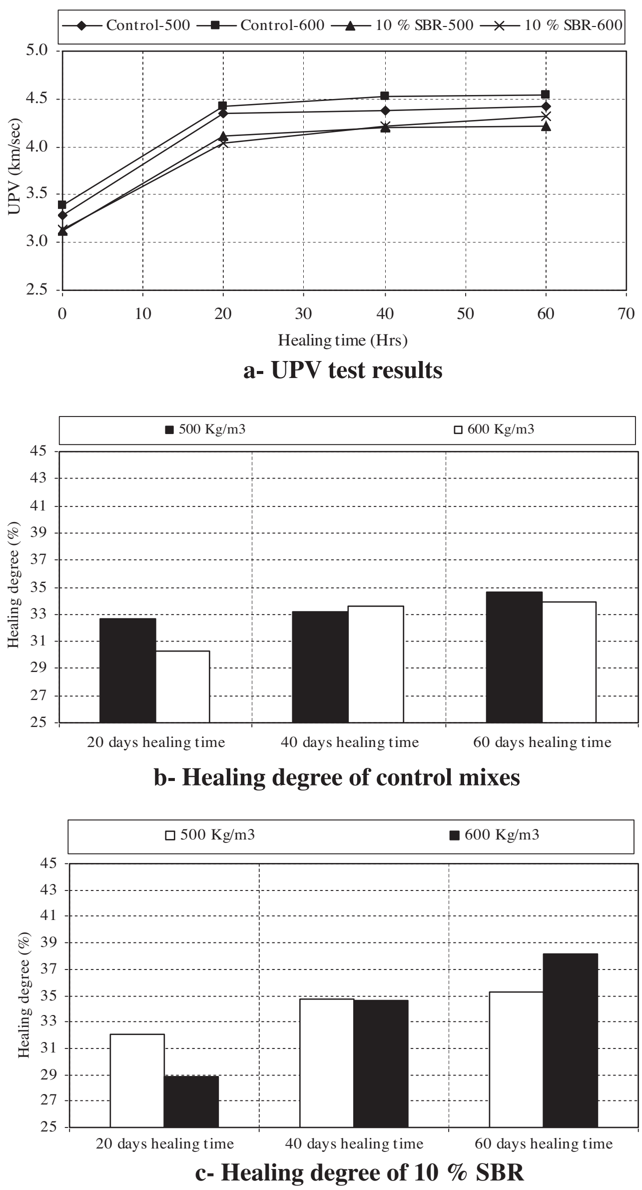


Figure 6 Effect of cement content on UPV and healing degree at 30.0% damage level.

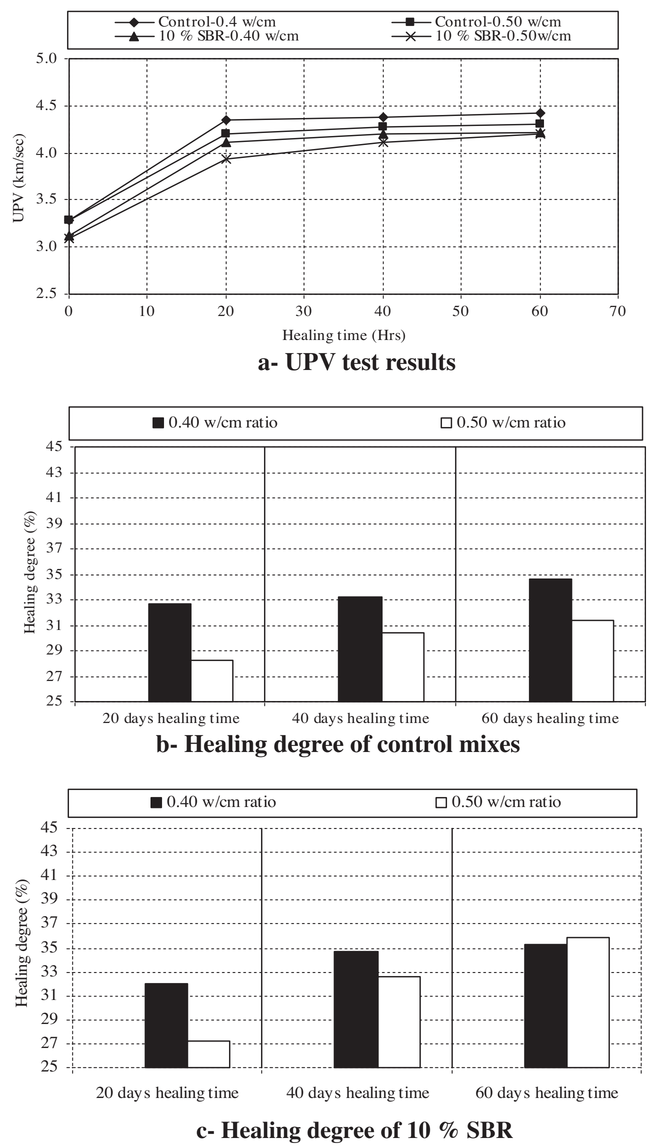


Figure 7 Effect of w/cm ratio on UPV and healing degree at 30.0% damage level.

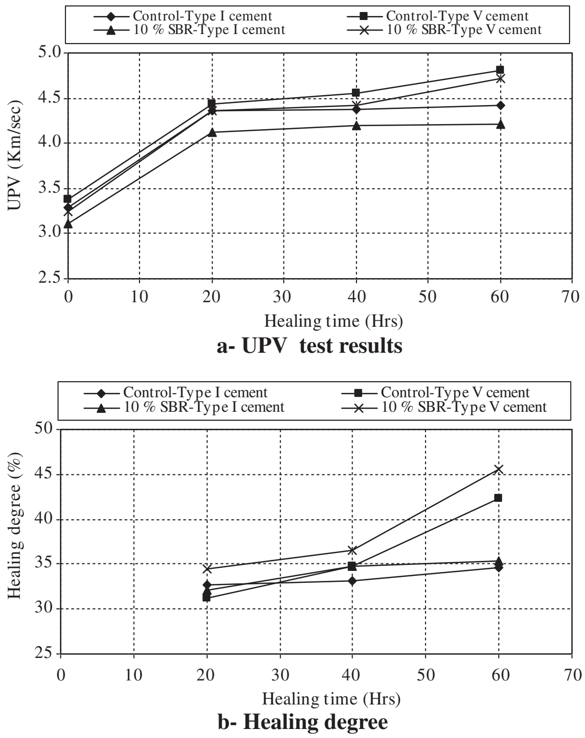


Figure 8 Effect of cement type on UPV and healing degree at 30.0% damage level.

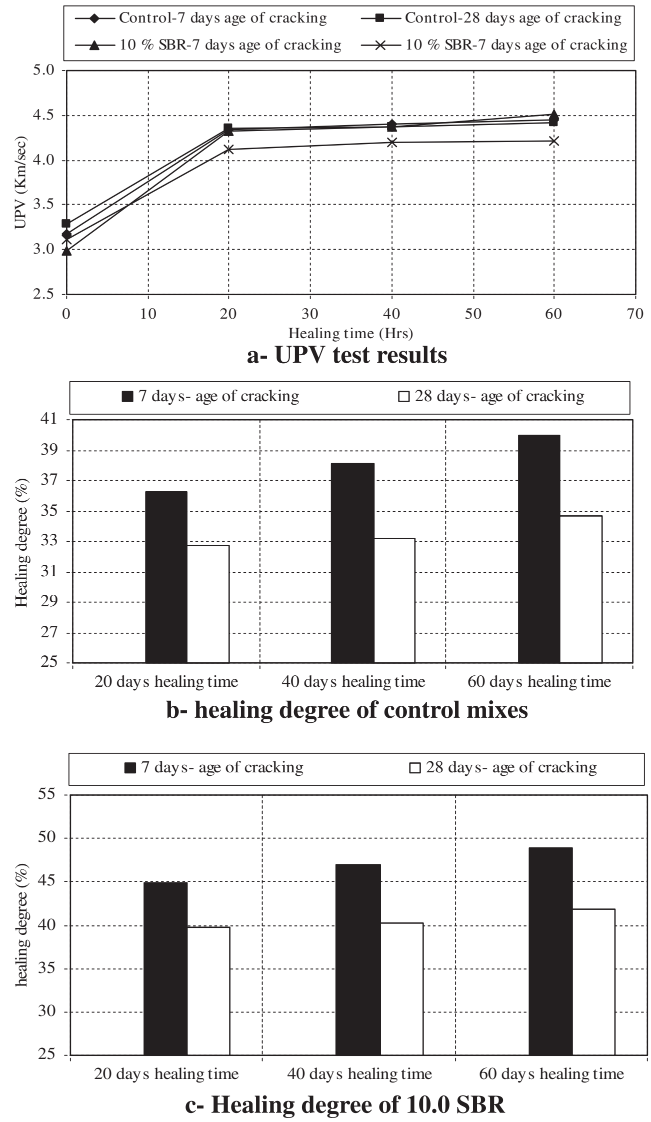


Figure 9 Effect of damage age on UPV and healing degree at 30.0% damage level.

specimens with w/cm ratio of 0.40 with 0.0% and 10.0% styrene butadiene rubber as shown in Fig. 3. This test was mainly carried out to estimate degree of cement hydration which is a function of amount of hydrated and unhydrated cement particles. Determination of degree of hydration (α) depends on the mass loss between 145 and 1000 C ($W_{n(t)}$), and ratio of non-evaporable water corresponding to full hydration ($W_{n(\infty)}$). The value of $W_{n(\infty)}$ is 0.25 for typical Type I Portland cement. Degree of hydration can be calculated as follows [2]:

$$\alpha = W_{n(t)}/(W_{n(\infty)} \times Mc) \tag{3}$$

where Mc is the initial mass of cement sample in gram.

Fig. 4 shows the degree of hydration of mixes with 0.0% and 10.0% styrene butadiene rubber. From this figure, one can conclude that the use of styrene butadiene rubber decreases the degree of hydration which means increase of amount of unhydrated cement particles. This explains why concrete mixes with styrene butadiene rubber yields higher healing degree.

The pervious trend of concrete modified by styrene butadiene rubber is the same of concrete modified by acrylic as shown in Fig. 5. From this figure, it is observed that the increase of acrylic dose increases healing degree when it is compared with control mix.

3.4. Effect of cement content

Fig. 6 shows the effect of cement content on the predicted ultrasonic pulse velocity at 30.0% damage level for concrete with and without styrene butadiene rubber. Form this figure; it is clear that cement content has insignificant effect on healing process for concrete with and without styrene butadiene rubber.

3.5. Effect of w/cm

The effect of w/cm ratio on self healing process is shown in Fig. 7 at 30.0% damage level. From this figure, at the same healing time, the increase of w/cm ratio decreases ultrasonic pulse velocity for control mix or concrete mix modified with 10.0% styrene butadiene rubber. Also, healing degree decreases with the increases of w/cm ratio. This may be due to the probability of the presence of unhydrated cement particles increases with the decrease of w/cm ratio. This assumption aggress with test results of Bentz and Garboczi [3]. Bentz and Garboczi found that degree of cement hydration increased as w/cm ratio increased. The pervious trend is the same for concrete made with and without styrene butadiene rubber.

3.6. Effect of cement type

The effect of cement type on the healing process for control and concrete mix modified by 10.0% styrene butadiene rubber at 30.0% damage level is shown in Fig. 8. The figure demonstrates thar, for concrete with and without styrene butadiene rubber, the healing degree of concrete made with Type V Portland cement is higher than that of concrete mixes made with Type I Portland cement. This trend becomes very clear after 60 days of healing time compared with 20 and 40 days. This may be due to the degree of hydration of Type V Portland cement takes longer time than that of Type I Portland cement.

3.7. Effect of age of damage

The effect of age of damage on healing process is shown in Fig. 9. From this figure, it is noticeable that the increase of age of damage decreases the healing degree. This trend is the same for concrete with and without 10.0% styrene butadiene rubber. This trend agrees with the experimental test results of Zhong and Yao for normal and high strength concrete [12].

4. Conclusions

Based on this experimental study, the following conclusions can be drawn:

1- Healing process exists in polymer modified concrete as in traditional concrete.
2- Immersion of concrete without polymers in water up to 20 days is enough to achieve most of healing process while for polymer modified concrete this process needs more immersion period.
3- The increase of polymer content either styrene butadiene rubber or acrylic increases healing degree compared with control mixes without polymers.
4- Healing process depends on the polymer type.
5- The cement content has insignificant effect on the self healing efficiency for concrete with or without polymer.
6- The increase of w/cm ratio decreases healing degree for concrete with or without polymer.
7- Concrete mixes made with Type V Portland cement give higher healing degrees compared with concrete mixes made with Type I Portland cement.
8- The increase of damage age decreases the healing efficiency for concrete made with or without polymer.

References

[1] AC1 548.3R, "Polymer modified concrete", American Concrete Institute, 2003.
[2] Hassan, Properties of latex modified mortar and concrete, Ms.C Thesis, Alexandria University, 2010.
[3] D. Bentz, E. Garboczi, Modelling leaching of calcium hydroxide from cement paste; effects on pore space percolation and diffusivity, Materials and Structures 25 (1992), 52:533.
[4] C. Edvardsen, Water permeability and autogenous healing of crack in concrete, ACI Materials Journal 4 (1988) 448–454.
[5] S.A. Granger, M. Loukili, G. Pijaudier-Cabot, G. Chanvillard, Experimental characterization of self-healing of cracks in an ultra high performance cementitious materials: mechanical tests and acoustic emission analysis, Cement and Concrete Research 37 (2007) 519–527.
[6] S. Gray, Autogenous healing of fiber/matrix interfacial bond in fiber-reinforced mortar, Cement and Concrete Research 14 (1984) 315–317.
[7] Ohama Y., 1987. Handbook of polymer modified concrete and mortars-properties and process technology. Nihon university, Japan, Noyes publications park Ridge, New Jersey, USA.
[8] S. Qian, J. Zhou, M. Rooij, E. Schlangen, G. Ye, K. van Breugel, Self-healing behavior of strain hardening cementitious composites incorporating local waste materials, Cement and Concrete Composites 31 (2009) 613–621.
[9] M. Sahmaran, S. Keskin, G. Ozerkan, I. Yaman, Self- healing of mechanically-loaded self consolidating concretes with high volumes of fly ash, Cement and Concrete Composites 30 (2008) 872–879.
[10] F. Shaker, A. El-Dieb, M. Reda, Durability of styrene-butadiene latex modified concrete, Cement and Concrete Research 27 (1997) 711–720.
[11] P. Termkhajornkit, T. Nawa, Y. Yamashiro, T. Saito, Self-healing ability of fly ash-cement systems, Cement and Concrete Composites 31 (2009) 195–203.
[12] W. Zhong, W. Yao, Influence of damage degree on self-healing of concrete, Construction and Building Materials 22 (2008) 1137–1142.